ROTATION AND MASS OF THE Sa GALAXY, NGC 681

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ABSTRACT

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The Sa galaxy NGC 681 has been found to have emitting gas throughout its disk component so that a rotation curve, mass distribution, and mass within a radius of 5250 pc have been derived. These prove to be very similar to those found for Sc galaxies, despite the Sa classification and the structural similarity of this galaxy to the well-known NGC 4594. The mass of NGC 681 is 1.9×10^{10} $M_\odot$, the mean density 1.0×10^{-23} gm/cm^3, and the mass-to-light ratio 3.6.

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It is well known that there is much less ionized gas present in elliptical, S0 and Sa galaxies than in Sb, Sc, and irregular systems. In an attempt to study the conditions of excitation in the interstellar gas through the whole range of Hubble types we have made observations of a considerable number of spiral and irregular galaxies (Burbidge and Burbidge 1962). To extend this study to other types we took spectra in the red wavelength region of a considerable number of elliptical, S0, and Sa galaxies listed by Humason, Mayall, and Sandage (1956) in which Humason had noted that the emission feature [O II] $\lambda 3727$ is present. The results of this survey will be reported in another paper. Among the galaxies included in this study was NGC 681 which is classified Sa and which bears a striking resemblance to NGC 4594, the famous Sombrero Nebula.

A plate of NGC 681 taken at the prime focus of the McDonald 82-inch telescope is shown in Figure 1. It was found that, as well as showing emission lines of Hα and [N II] $\lambda 6583$ in the central bulge, the emitting gas could be detected far out in the disk. The Lick spectrogram described below showed that these two emission lines are of approximately equal intensity in the center of the galaxy, but have the usual ratio of Hα/[N II] ≈ 3 in the disk, indicating that they are excited by the usual radiative mechanism operating in spiral arms. Thus it is clear that the furthest out knots are in fact H II regions containing highly luminous O and B stars. This situation is to be contrasted with that in NGC 4594 where Münch (1962) has obtained spectra of apparently similar structures in the arms, but has found no emission features. Thus he has concluded that these cannot be H II regions but must be star clusters which do not supply enough ultra-violet radiation to ionize the gas, or in which very little gas is present.

The importance of our discovery of extended emission features in NGC 681 is that we can obtain a rotation curve and hence a mass and mass distribution for a galaxy of this type. The first spectrum was taken with the B spectrograph at the prime focus of the 82-inch telescope of the McDonald Observatory. This exposure was made when the moon was more than half full and has therefore a considerable background spectrum of scattered moonlight; consequently the plate was not suitable for accurate measurement. It did clearly show, however, an extended and inclined emission line that was presumably Hα with a considerable velocity gradient.

On December 4, 1964, a spectrum of 4 hours' expsoure was taken with the prime focus spectrograph of the Lick 120-inch telescope, with the slit set along the major axis in position angle 64°, and with the grating and camera combination giving a dispersion of 190 Å/mm at Hα. The velocities measured from this spectrogram alone are plotted in Figure 2, and the rotation curve obtained by folding these measures about a central velocity of +1705 km/sec relative to the local standard of rest is shown in Figure 3. Two smooth curves have been fitted to these points using the usual polynomial solution (cf. Burbidge, Burbidge, and Prendergast 1959), with four and six parameters, respectively.

The recession velocity of the center of mass of this galaxy corrected for galactic rotation is +1727 km/sec. This value can be compared with the value of +1768 km/sec obtained by Humason (Humason et al. 1956). For this redshift, with a value of the Hubble constant of 75 km/sec per Mpc, the distance of NGC 681 is then 23 Mpc and at this distance 1" = 111.7 pc. Since the observations extend to a distance of 47" from the center, this corresponds in linear dimensions to a radius of 5250 pc. It should be added here that the total diameter out to which luminosity can be detected on the direct plate is approximately 55" or 6140 pc. The total mass of the system and the central density, calculated by our usual method, are shown in Table 1 as a function of the number of parameters in the solution, for values of c/a of 1/4, 1/5, and 1/8.

The galaxy is very nearly edge-on. We concluded that the correction factor to be applied to the velocities for inclination of the galaxy was therefore very nearly unity. From the direct plate we found, by estimating the major and minor axes of the flat component, that the inclination $\xi = 81^\circ$ so that the correction factor for the mass equals $\operatorname{cosec}^2 \xi = 1.02$; this has been applied in deriving the values shown in Table 1. It will be seen from Table 1 that the mass does not depend sensitively on the assumed value of c/a and we may conclude that the total mass contained within a radius of 5.25 kpc is $1.9 \pm 0.2 \times 10^{10}\ M_\odot$. Since the galaxy has a large central bulge, a rather large value of c/a is indicated. The densities normalized to unity at the center are plotted against distance from the center in Figure 5, for the 4- and 6-parameter solutions, both for c/a = 1/4. For c/a = 1/4 the mean density of the galaxy within the observed radius is 1.0×10^{-23} gm/cm^3. For this galaxy $m_{pg} = 12.8$ and with a distance modulus of 31.8 corresponding to a distance of 23 Mpc, $M_{pg} = -19.0$. Thus the photographic mass-to-light ratio is 3.6.

We have obtained rotation curves for a considerable number of Sb and Sc galaxies. Three quantities which have been measured in all of these are the forms of the rotation curves, the total masses, and the mean densities. In all of these respects this Sa galaxy is indistinguishable from other galaxies of very different forms. To show this we give in Table 2 data concerning the total mass, the radius out to which the mass was measured, and the mean densities for a number of Sc and Sb galaxies. In Figure 4 we show the rotation curve for NGC 1084, an Sc system (Burbidge, Burbidge, and Prendergast 1963), to show the form of the rotation curve and its similarity to that for NGC 681.

Editor: Although Fig. 4 is not referred to until this point, would you please print it on the same page as Fig. 3?

While NGC 681 has all of these physical parameters which are indistinguishable from later type spiral galaxies, it appears to be very similar in structural details to NGC 4594 though it is smaller, less luminous, and presumably less massive. From the data given by Sandage (1961) for NGC 4594 we find that this galaxy has an absolute magnitude of -21.5, compared with -19 for NGC 681. The apparent linear dimensions out to the points of lowest luminosity which can be easily distinguished on direct plates are 11.7 kpc (NGC 4594) and 5.3 kpc (NGC 681). Pease (1916) noted that the absorption lines in the spectrum of NGC 4594 could be measured out to 2' from the center, and had an inclination with a slope of 2.78 km/sec per second of arc. This gives a rough Keplerian estimate for the mass of NGC 4594 of 1.7×10^{11} $M_{\odot}$ within 7500 pc of the center (i.e., within about 2/3 of the luminous extent clearly visible on direct plates). If the mass-to-light ratios for these two galaxies were comparable the total mass of NGC 4594 would have to be about 2×10^{11} $M_{\odot}$ while if the mass-to-light ratio for NGC 4594 were ~ 10 as is often thought reasonable for Sa systems it would have to be about 6×10^{11} $M_{\odot}$.

We believe that these results which we have obtained for NGC 681 are of considerable importance for the ideas of the evolution of galaxies. We had earlier (Burbidge et al. 1963) remarked on the similarity in form between the two fat-armed Sc galaxies NGC 157 and NGC 1084 and their very similarly-shaped rotation curves, and the contrast between these and NGC 5055, an Sc galaxy with thin, much-wound spiral arms and a rather different rotation curve resulting from a much greater central concentration of mass. It had seemed that the visual form of a galaxy might be well correlated with the shape of its rotation curve. The results for NGC 681 show that this is not the case.

Further, one argument that has been advanced by ourselves, among others, against the idea that galaxies can evolve through a sequence of types from irregulars to ellipticals has been that Sa and elliptical galaxies which are thought to contain older and more evolved stellar populations have larger masses than the less evolved galaxies and so could not have proceeded through this sequence without the accretion of mass. While this may well be generally the case, all the parameters associated with NGC 681 and specifically its mass, rotation curve, and relative density curve suggest that it may well have evolved through this sequence.

Finally, we note that little can be said about the population of the large central bulge of NGC 681. The Lick spectrogram showed the blend of the Na I D lines at $\lambda 5893$ in absorption in the strip of continuum from the central region of the galaxy, but this refers only to a distance of $3\frac{1}{2}''$ each side of the center, i.e., a radius of 400 pc. This absorption feature is inclined, indicating a velocity gradient of about the same magnitude as that shown by the emission lines. It was not, however, measured, as the spectrogram is not in best focus here, the focus having been set for the red spectral region. This was the only absorption feature seen in the range 5800 - 6800 Å (there is a strong airglow spectrum on our plate). Humason's spectral type of G5 suggests that the stellar population is that usually found in the nuclei of SO, Sa, and E galaxies. The D lines are blended on our plate but do not show great additional broadening, so we can infer that the velocity dispersion of the stars in the bulge component, which has little flattening, is not inconsistent with the mass that we have derived.

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TABLE 1

MASS AND CENTRAL DENSITY FROM VARIOUS SOLUTIONS

c/a	No. of Parameters	$M/M_{\odot} \times 10^{-10}$	Central Density $\rho_o \times 10^{22}$ gm/cm^3
1/4	3	2.01	1.09
1/4	4	2.04	1.00
1/4	5	2.09	1.12
1/4	6	1.74	2.39
1/4	7	1.64	1.79
1/5	3	1.99	1.30
1/5	4	2.02	1.19
1/5	5	2.05	1.32
1/5	6	1.86	2.84
1/5	7	1.81	2.13
1/8	3	1.95	1.92
1/8	4	1.97	1.76
1/8	5	1.98	1.96
1/8	6	1.92	4.19
1/8	7	1.91	3.14

TABLE 2

MASSES, RADII, AND MEAN DENSITIES OF NGC 681

TOGETHER WITH SOME Sc AND Sb GALAXIES

Galaxy	Type	$M/M_{\odot}$ $\times 10^{-10}$	Radius kpc	Mean Density* $\times 10^{23}$ gm/cm^3
NGC 681	Sa	1.9	5.2	1.0
NGC 157	Sc	6.0	9.3	1.2
NGC 253	Sc	20	8	6.8
NGC 1084	Sc	1.6	5.1	2.0
NGC 1792	Sc	1.8	4.5	2.4
NGC 2146	Sbc	1.8	2.3	4.5
NGC 2903	Sc	3.7	4.4	6.7
NGC 3521	Sb	8.0	7.1	3.7
NGC 3556	Sc	1.4	7.5	0.4
NGC 4258	Sb	8.2	7.0	2.6
NGC 5005	Sb	7.0	6.0	5.4
NGC 5055	Sbc	7.6	10	1.9
NGC 6503	Sc	0,13	1.5	6.8
NGC 7331	Sb	8.0	10	1.6

* These mean densities refer only to the observed masses in Column 3 and the radii within which the observations were made, given in Column 4; they should be systematically consistent as they have all been derived by us using the same method of analysis.

FIGURE CAPTIONS

Fig. 1 - NGC 681, photographed at prime focus of 82-inch telescope at the McDonald Observatory of the University of Texas, on baked Kodak IIa-O plate through a Schott GG13 filter. Inset is a dark print from same plate to show center. South is at top, east at left. Scale: 1 mm = 2.7".

Fig. 2 - Observed velocities relative to local standard of rest plotted against distance from center of NGC 681.

Fig. 3 - Velocity measures folded about central velocity of +1705 km/sec. Curves are polynomial solutions with 4 and 6 parameters, respectively, fitted to the observed points; velocities have not been corrected for inclination of plane of galaxy to line of sight.

Fig. 4 - Rotation curve of the Sc galaxy NGC 1084, showing the great similarity with the rotation curve of NGC 681 given in Fig. 3.

Fig. 5 - Density relative to central value, computed for c/a = 1/4 with 4 and 6 parameters, respectively, plotted against distance from the center of NGC 681.

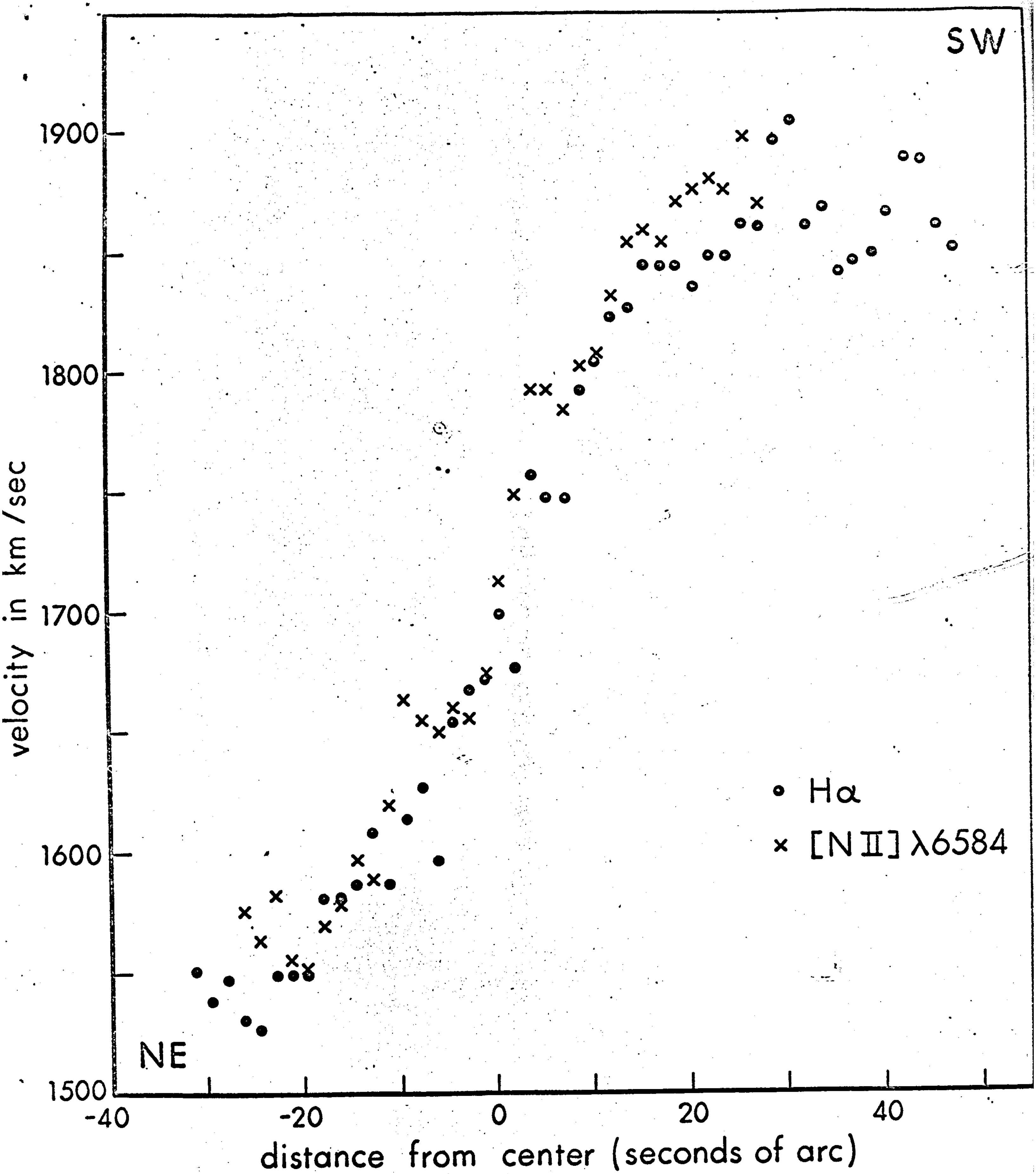


Fig. 2. Burbidge Burbidge and Prendergast

NGC 681

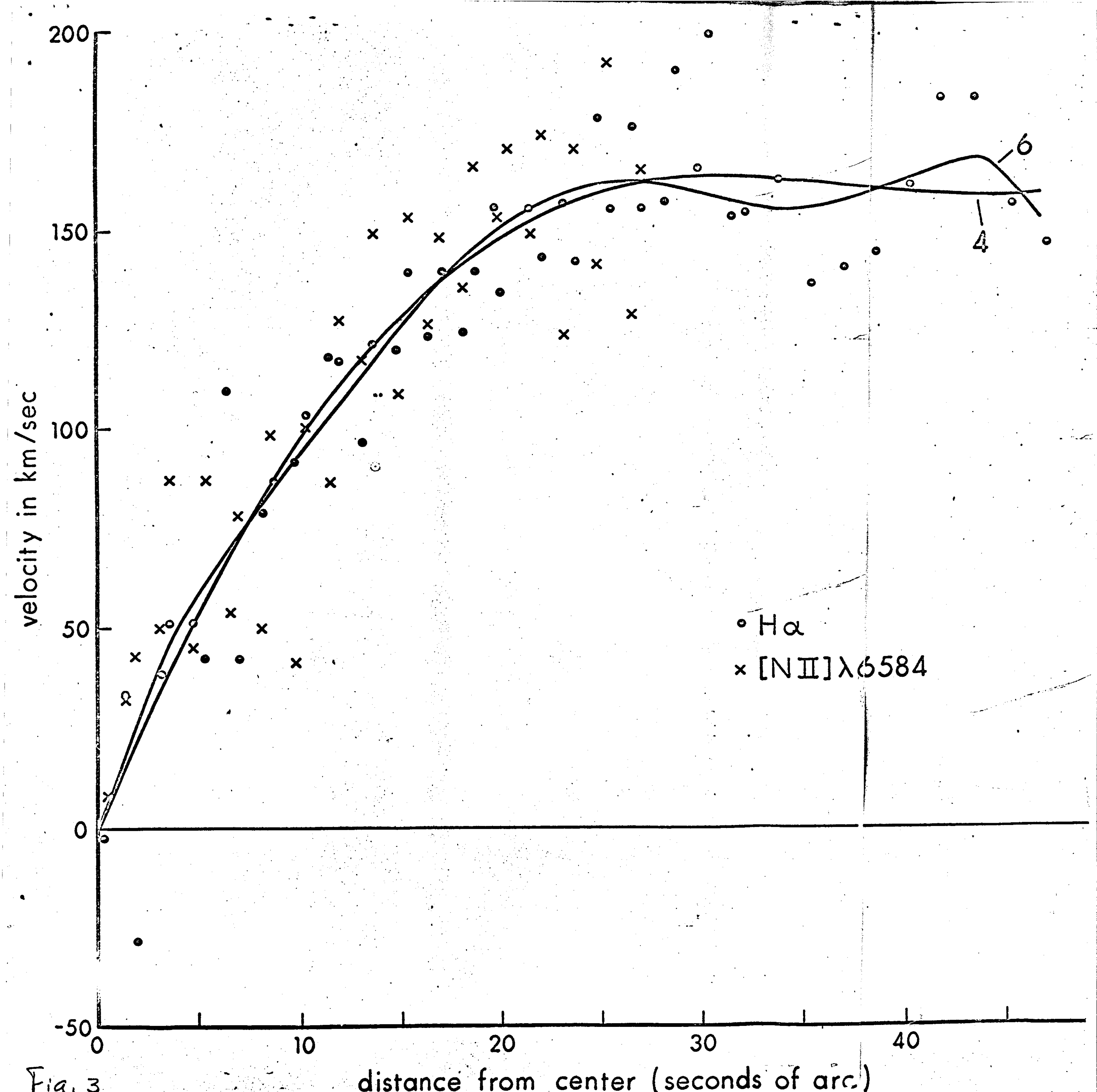
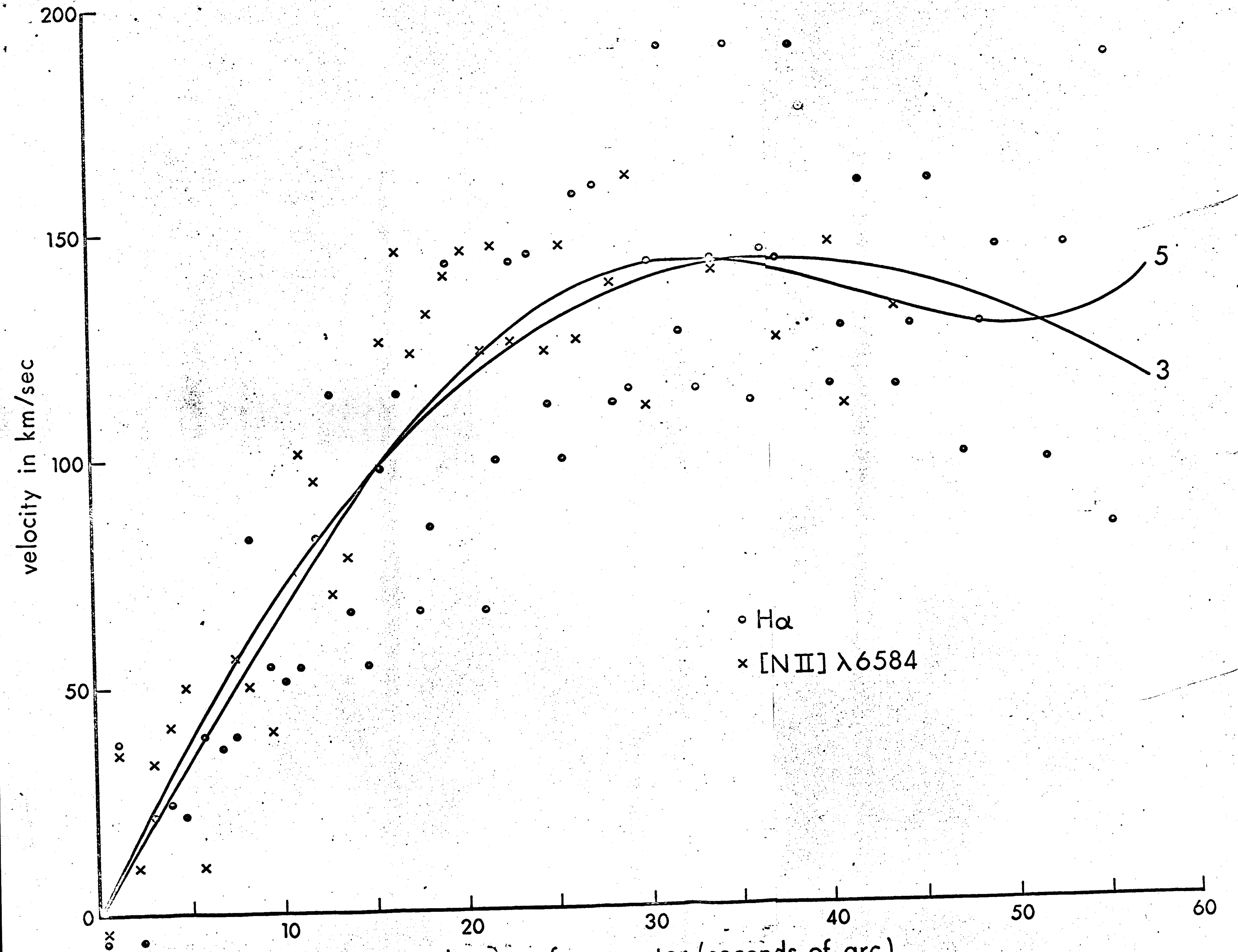

200
150
100
50
0
-50
velocity in km/sec
0
10
20
30
40
distance from center (seconds of arc)
Hα
[N II] λ6584
6
4

Fig. 3



velocity in km/sec
200
150
100
50
0
10
20
30
40
50
60
5
3
Hα
[N II] λ6584

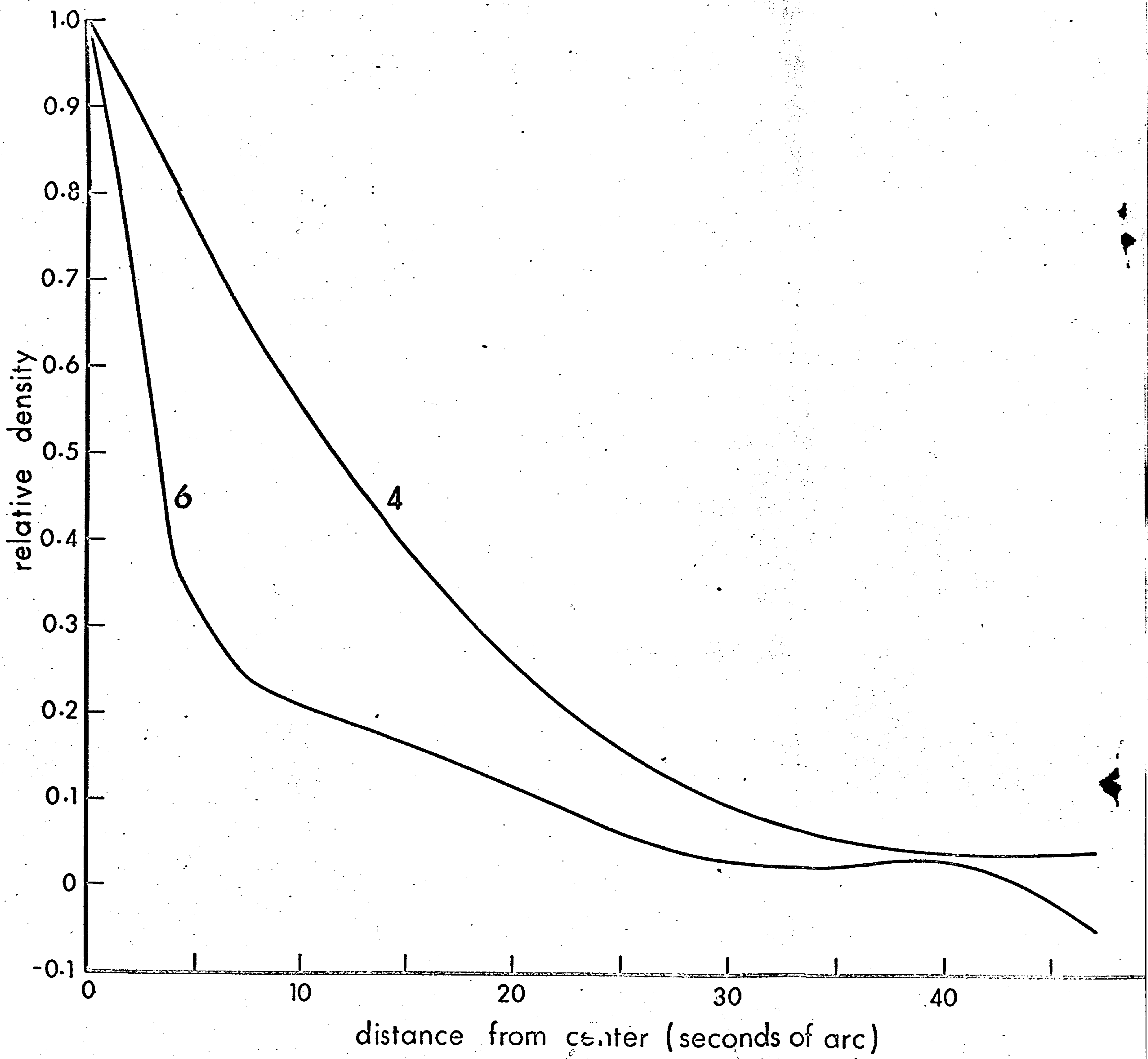


Fig. 5. Burbidge, Burbidge and Prendergast [illegible]